# Shoaling Wave Energy Dissipation in
# Turbulent Bottom Boundary Layers

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## LONG-TERM GOALS

The long term goal is to increase the understanding and predictive capability for effects of turbulent bottom boundary layers on shoaling wave fields.

## SCIENTIFIC OBJECTIVES

The primary objectives are to make direct estimates of wave energy dissipation rates that occur in the boundary layer for different wave field conditions and to use three-dimensional direct numerical simulations to evaluate one-dimensional eddy viscosity models such as proposed by Trowbridge and Madsen (1984) and Fredsoe and Deigaard (1992).  We are also examining the vertical transport of mass and momentum within the boundary layer by turbulent diffusion and differences between oscillatory boundary layers and steady uni-directional flows.

## APPROACH

The work involves theoretical analysis, numerical computations, and comparison with field and laboratory results.  The primary experimental tools are three-dimensional direct numerical simulations (DNS) (Slinn and Riley, 1998) and large eddy simulations (LES) of turbulent flows occurring in the wave bottom boundary layer.   The model resolves the relevant scales of motion in the strong shear layer at the sea floor.

## WORK COMPLETED

Analysis of numerical experiments of the wave bottom boundary layer for flat bottom conditions has been completed.  Selected results are presented below.  The three major accomplishments this year have been:

1.  Validation of the model by comparison with laboratory and analytical results.

2.  Development of accurate approximate methods for estimating dissipation rates in the bottom boundary layer from limited measurements such as vertical velocity profiles.

3.  Determination of actual spatially and temporally varying vertical eddy diffusivities within the turbulent boundary layers from the simulations.

Journal articles describing the details of the numerical model (Slinn and Riley, JCP, 1998a) application of the model for a stratified oscillatory boundary layer (Slinn and Riley, TCFD, 1998b), and numerical modeling of wave induced currents (Slinn, et al., JGR, 1998a) were published in FY98 and partially supported under this project.

**RESULTS**

The numerical model is based upon the full Navier-Stokes equations with an external pressure gradient term dp/dx added to the x-momentum equation to force current external to the boundary layer. The model is periodic in the x and y-directions and an open boundary condition at the upper boundary (Durran et al., 1993) that absorbs disturbances propagating upwards from the boundary layer. The time step is adjusted throughout the calculation to ensure numerical stability but averages approximately 5,000 time steps per second for these calculations. A simple sub-grid scale model is implemented for the large-eddy simulations. Additional dissipation is added to the smallest-resolvable scales by filtering high wave number disturbances.

Typical boundary layer thicknesses are of the order of 0.5 - 5 cm and the wave induced current speeds above the sea bed are commonly between 10 and 100 cm/s, depending on wave field characteristics. These values lead to typical boundary layer Reynolds numbers, Re = U d / v, between 500 and 50,000. For a smooth bottom, transition to turbulence occurs for approximately Re = 3000 depending on the wave frequency. Numerical simulations have been conducted above and below the transitional value for the Reynolds number. It has been confirmed that flows with less than 70% of the transitional value remain laminar (with resulting boundary layer thicknesses of approximately 0.5 cm), while flows with approximately 150% of the transitional value burst into turbulence (with resulting boundary layer thicknesses of approximately 2-5 cm, depending on the wave frequency and maximum current velocity.)

Dissipation rate contours during a burst of turbulence are shown in Figure 1 for an experiment with a maximum current speed of 0.8 m/s and a wave period of 5 s. The top panel of Figure 1 shows a plan view of the x-y plane parallel to the wall at a height z = 0.27 cm. The bottom panel of Figure1 shows the x-z plane located at y = 3.75 cm. In this example the boundary layer thickness increases from approximately 0.5 cm during periods of laminar flow to 2-4 cm during active turbulence, varying with each event.

The turbulence is episodic in nature, going through mixing phases approximately twice per wave period. The horizontally averaged turbulent kinetic energy is shown as a function of height and time in Figure 2. During phases of flow deceleration the boundary layer destabilizes and patches of turbulence originating near the wall spread across the domain engulfing surrounding fluid. The turbulence achieves its maximum intensity just after flow reversal and decays rapidly as the flow accelerates in the opposite direction, exhibiting characteristic streaks in the along-stream direction in
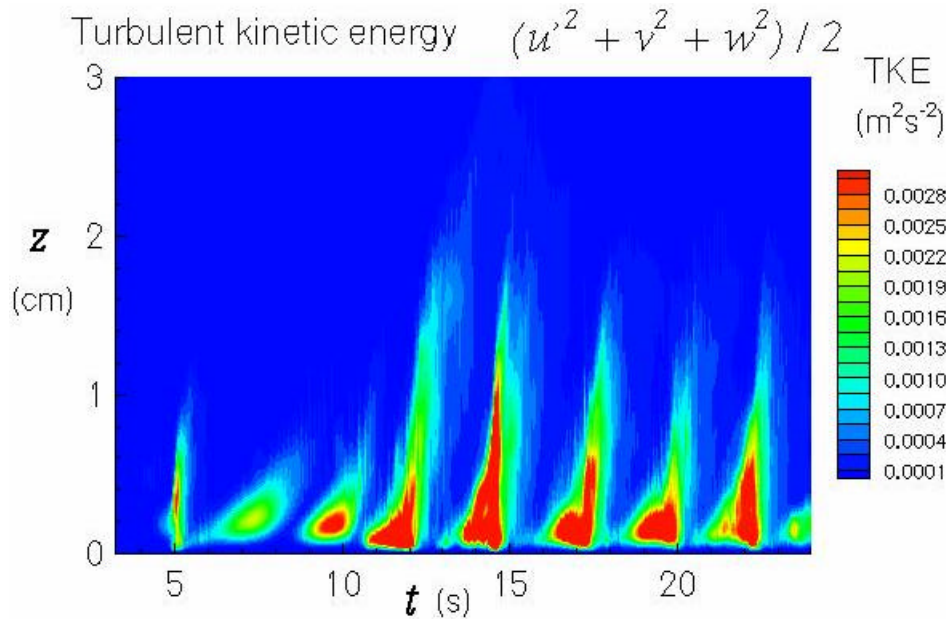
velocity, dissipation rate, and wall shear stress fields. Eddy diameters during turbulence scale with the distance from the wall but are commonly observed in the range between 0.2 and 1.5 cm. These features are well resolved in this experiment with a grid spacing of approximately 0.03 cm.



z = 0.27 cm
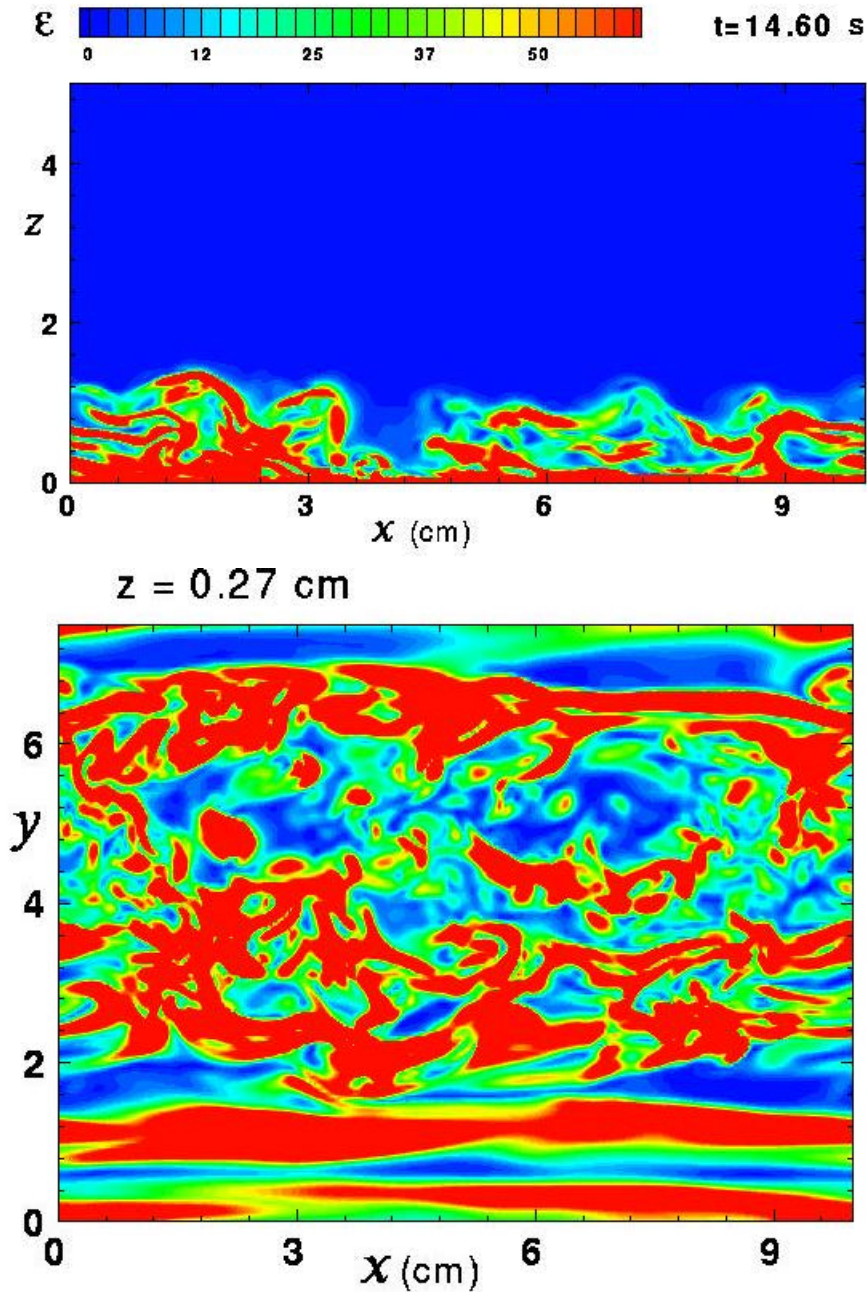


We use Lagrangian particles in the flow to determine the vertical dependence of the turbulent diffusion coefficients from the DNS model. Thousands of ``particles'' are released in a three-dimensional lattice before transition and the particle positions are integrated forward in time and advected by the local fluid motions. As time progresses the Lagrangian particles are distributed

throughout the domain and the time-averaged turbulent diffusion coefficient, is estimated from the mean vertical particle displacement, (Tennekes and Lumley, 1972). We find both that the diffusion coefficient is a function of time (as suggested by Trowbridge and Madsen, 1984) and that it is more closely approximated by a quadratic (Fredsoe and Deigaard, 1992) than a linear function. We are currently comparing the impact of different formulas for the eddy diffusivity in one-dimensional boundary layer models to determine improved approximations for mean velocity profiles.

Our results are in qualitative agreement with related laboratory and field studies and show similar development of features such as boundary layer current velocities, flow dynamics, and transition Reynolds numbers. The simulations have demonstrated the capability to study this complex flow using our 3-D boundary layer model. We plan to refine and enlarge these simulations as we progress and are confident that DNS and LES, coupled with theoretical and data analysis, will add significant new understanding to the wave bottom boundary layer.

Turbulent kinetic energy $(u'^2 + v'^2 + w'^2)/2$

TKE $(m^2 s^{-2})$

0.0028
0.0025
0.0022
0.0019
0.0016
0.0013
0.0010
0.0007
0.0004
0.0001

## IMPACT/APPLICATION

Small-scale boundary layer processes at the sea bed in shallow water are strongly influenced by wave motions and are key to understanding issues such as beach erosion and protection, bottom morphology, water clarity, mine burial, surface wave energy budgets, and bottom friction experienced by mean currents. Our work is an effective means of developing and testing parameterizations for small-scale processes that must be considered in larger scale modeling. In addition, the rapid decay of the turbulence in the boundary layer during periods of flow acceleration suggests applications in drag reduction by radially oscillating an outer shell on a cylindrical vessel such as a AUV or torpedo while moving through the water. This hypothesis will be illuminated in our future work as we study the oscillatory wave boundary layers together with boundary layers from steady mean currents with different directional orientations.

**TRANSITIONS**

FY98 has been the first year of this project and we have focused on validating our model and exploring different parameter ranges of wave frequency and current forcing. We also tested modifications to our model to allow implementation of a rippled seabed but will defer examination of those cases until a later stage. The major transition during this year was Slinn moving from a Post-Doc position at Oregon State University to an Assistant Professor in the Ocean Engineering Department at Florida Atlantic University.

**RELATED PROJECTS**

This project is part of the Shoaling Surface Waves DRI that seeks increased understanding of the shoaling wave energy budget. The most closely related project is being conducted by Stanton and Thornton, of the Naval Postgraduate School who are making measurements of instantaneous velocity profiles in the wave bottom boundary layer using acoustic Doppler velocimetry. They obtain time series of $u(z,t)$, $v(z,t)$, and $w(z,t)$ which are used to estimate dissipation rates in the boundary layer. Following approximate methods developed by Smyth (1998), we have compared volume averaged dissipation rates from the numerical simulations, in which terms of the dissipation rate are calculated explicitly, with estimates derived exclusively from time series of $u(z,t)$, $v(z,t)$ and $w(z,t)$ as will be available from the field data. Different approximations can be used to estimate unknown terms from the full dissipation rate tensor. We have been able to show that several approximate methods yield reasonably accurate results. We are currently testing the estimation techniques for simulations with stronger turbulent events to assess the generality of these results.

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